Filtering techniques for the removal of ventilator artefact in oesophageal pulse oximetry

K. Shafqat · D. P. Jones · R. M. Langford · P. A. Kyriacou

Abstract The oesophagus has been shown to be a reliable site for monitoring blood oxygen saturation (SpO_2). However, the photoplethysmographic (PPG) signals from the lower oesophagus are frequently contaminated by a ventilator artefact making the estimation of SpO_2 impossible. A 776th order finite impulse response (FIR) filter and a 695th order interpolated finite impulse response (IFIR) filter were implemented to suppress the artefact. Both filters attenuated the ventilator artefact satisfactorily without distorting the morphology of the PPG when processing recorded data from ten cardiopulmonary bypass patients. The IFIR filter was the better since it conformed more closely to the desired filter specifications and allowed real-time processing. The average improvements in signal-to-noise ratio (SNR) achieved by the FIR and IFIR filters for the fundamental component of the red PPG signals with respect to the fundamental component of the artefact were 57.96 and 60.60 dB, respectively. The corresponding average improvements achieved by the FIR and IFIR filters for the infrared PPG signals were 54.83 and 60.96 dB, respectively. Both filters were also compared with their equivalent tenth order Butterworth filters. The average SNR improvements for the FIR and IFIR filters were significantly higher than those for the Butterworth filters.

Keywords Pulse oximetry · Photoplethysmography · Oesophagus · Artefact · Filtering

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1 Introduction

Pulse oximetry relies on the presence of adequate peripheral arterial pulsations, which are detected as photoplethysmographic (PPG) signals. When peripheral perfusion is poor, as in states of hypovolaemia, hypothermia, vasoconstriction and low cardiac output, oxygenation readings become extremely unreliable or cease [1, 6, 7]. Pulse oximeters fail in these circumstances because the sensors are usually placed on the most peripheral parts of the body such as the finger or toe where pulsatile flow is most easily compromised.

The human oesophagus has been shown to be a more reliable alternative site for monitoring arterial blood oxygen saturation (SpO_2) by pulse oximetry in anaesthetised cardiothoracic patients and others [3–5]. Although many successful measurements of SpO_2 have been made in the oesophagus, it has only been feasible to measure SpO_2 in the middle to upper oesophagus since the ac PPG signals from the lower oesophagus have been frequently contaminated by an artefact synchronous with the period of the mechanical ventilator. The magnitude of this artefact varied from patient to patient and it also depended on the depth of the measurement site. The SpO_2 estimation was accurate only when the artefact was less than 40% of the magnitude of the oesophageal ac PPG signal. In the lower part of the oesophagus, where the ac PPG signals were of large amplitude [3], the magnitude of the artefact was often more than that of the ac PPG signal making the estimation of SpO_2 impossible.

The present work describes the design and evaluation of filters for reducing the ventilator artefact. A filter that would eliminate or reduce the ventilator artefact to acceptable levels would allow the continuous and accurate estimation of SpO_2 from the entire length of the oesophagus and would also make the positioning of the probe an easier and less time consuming process.

2 Method

A finite impulse response (FIR) filter and an interpolated finite impulse response (IFIR) filter were designed for reducing the ventilator artefact. Both filters were evaluated offline and compared using recorded oesophageal PPG data contaminated with ventilator artefact that had been obtained from ten cardiopulmonary bypass surgery patients. These filters were also compared with infinite impulse response (IIR) bandpass Butterworth filters with equivalent cut-off frequencies.

The ventilator artefact in the PPG signal has its fundamental frequency component at approximately 0.2 Hz whereas the fundamental frequency component of the ac PPG signal is about 1 Hz. Hence, a bandpass digital filter having a lower cut-off frequency close to 1 Hz and a higher cut-off around 10 Hz should be able to reduce the artefact and also reject high frequency signals while retaining the ac PPG, as 95% of useful information in ac PPG signals lies below 10 Hz [2]. An FIR filter was preferred to an IIR filter because of its more linear phase characteristic. To minimize the computational requirements, an optimal filter design technique proposed by Parks and McClellan [8] was used. The PPG signals were originally sampled at 100 Hz and therefore the same sampling rate was used in the filter design. The filters were designed and implemented in a Matlab R13 environment to meet the following desirable specifications:

First cut-off = 0.87 Hz
Passband = 0.97–10.0 Hz
Second cut-off = 10.1 Hz
Minimum stopband attenuation = 80 dB (in both stopbands)
Maximum passband ripple = 0.5 dB.

2.1 Design of equiripple FIR filter

An Equiripple FIR filter that will satisfy the above specification is found to be a 2,774th order filter. Due to its very high order, this filter would be very difficult to implement in software for real time processing, therefore it was not considered. In order to reduce the filter order and allow real-time operation, the design specifications were relaxed slightly and a 776th order filter was implemented with the following specifications:

First cut-off = 0.5 Hz
Passband = 0.83–10.0 Hz
Second cut-off = 10.5 Hz
Minimum stopband attenuation = 80 dB (in both stopbands)
Maximum passband ripple = 1 dB.

2.2 Design of IFIR filter

In order to satisfy the original desirable filter specifications and also allow real time processing, an IFIR filter using a multirate processing technique was designed. To avoid rational factors in decimation and interpolation the signal was decimated to 25 Hz. To optimize the implementation, the decimation and interpolation were done in two stages. Equiripple filters of 8th and 60th order were used as image suppressors at 100 and 50 Hz, respectively. The designed IFIR filter meeting the ideal criteria was of 695th order.

2.3 Design of band pass equivalent Butterworth filters

A tenth order bandpass IIR Butterworth filter with lower and upper cut-off frequencies at 0.5 and 10.5 Hz, respectively, was designed to compare its performance with that of the 776th order Equiripple filter. Also, a second tenth order Butterworth filter with lower and upper cut-off frequencies at 0.87 and 10.1 Hz, respectively was designed to compare its performance with that of the 695th order IFIR filter. A tenth order Butterworth filter was chosen because higher order Butterworth filters caused unacceptable distortion of the PPG signal.

2.4 Data analysis and statistics

The performance of the FIR and IFIR filters was evaluated using recorded oesophageal PPG signals at both wavelengths (red and infrared) from ten adult patients undergoing cardiothoracic surgery. The signal-to-noise ratio (SNR) improvement for the fundamental component of the PPG signal with respect to the fundamental component of the artefact was calculated using the formula below:

$$\text{Total improvement} = [a_2(\text{dB}) - x_2(\text{dB})] - [a_1(\text{dB}) - x_1(\text{dB})],$$

where a_2 and x_2 are the magnitudes of the fundamental components of the PPG and the ventilator artefact in the filtered signal in dB, respectively, and a_1 and x_1 are the magnitudes of the fundamental components of the PPG and the ventilator artefact in dB, respectively, for the raw (unfiltered) signal.

The SNR improvement after filtering for the Equiripple FIR and IFIR filters and their corresponding IIR Butterworth filters were compared. The statistical significance of the difference, in each case, was assessed using a paired *t*-test with $p < 0.05$ taken as significant.

The effect of the filtering techniques on the estimation of SpO_2 using PPG signals unaffected by the ventilator artefact has also been evaluated. Photoplethysmographic signals, free of ventilator artefact, were processed using both the FIR and the IFIR filters and the SpO_2 values, before and after filtering, were estimated and compared.

3 Results

3.1 Results from the 776th order FIR Equiripple filter and comparison with an equivalent 10th order Butterworth filter

The magnitude and phase response of the 766th order Equiripple FIR filter described in Sect. 2.1 is shown in Fig. 1. The phase response of this filter is linear in the passband, hence there should be negligible phase distortion and the filtered signal should retain its morphology.

Typical results of the processing of recorded oesophageal PPG signals containing ventilator artefact, at both red and infrared wavelengths, using the Equiripple FIR filter and the equivalent tenth order Butterworth filter, are shown in Figs. 2 and 3. The raw PPG signals for the infrared and red wavelengths (Fig. 2a, 3a), are both dominated by the ventilator artefact which is almost 300% of the amplitude of the ac PPG signals.

The magnitude frequency spectrum of the raw red PPG signal and the spectrums obtained from the FIR and IFIR filtered red PPG signal are shown in Fig. 4.

The average attenuations, using the equation in Sect. 2.4, of the fundamental component of the artefact (at approximately 0.2 Hz) and the first harmonic of the artefact (at about 0.4 Hz) with respect to the fundamental component of the ac PPG signal at both the red and the infrared wavelength for the ten patients in this study are shown in Table 1

The results from the paired *t*-test indicated that the average SNR improvement for the FIR filter was significantly higher than that for the equivalent Butterworth filter for the fundamental and first harmonic of the artefact at both wavelengths. The mean differences in the SNR improvement between the FIR Equiripple and Butterworth filter for the fundamental and the first harmonic artefact components are shown in Table 2

3.2 Results from the implementation of the 695th order IFIR filter and comparison with an equivalent 10th order Butterworth filter

The magnitude and phase responses of the IFIR filter and the image suppressors used in the multirate implementation are shown in Fig. 5.

They are linear in the passband and therefore none of them should cause any major changes in the morphology of the PPG signal. The results obtained by processing the raw (corrupted) infrared (Fig. 2a) and red (Fig. 3a) PPG signals using the 695th order IFIR filter are shown in Figs. 6a and 7a, respectively. Whereas, part b of Figs. 6 and 7 shows the results obtained by using the tenth order Butterworth filter for the infrared and the red PPG signal, respectively.

The magnitude frequency spectra for the IFIR filtered red PPG signal is shown in Fig 4c. By comparing the spectrum of the corrupted red PPG signal shown in Fig. 4a with the spectrum of the IFIR filtered signal (Fig. 4c) it can be seen that the artefact is very well attenuated up to the fourth harmonic, which has a frequency of approximately 0.9 Hz. The average SNR improvement for the ten patients is summarized in Table 3

Similarly, results from the paired *t*-test between the IFIR filter and the equivalent Butterworth filter indicated that the average SNR improvement for the IFIR filter was significantly higher for both wavelengths. The mean differences in SNR improvement at each artefact component are presented in Table 4

Fig. 1 Magnitude and phase response of the 766th order Equiripple finite impulse response (FIR) filter

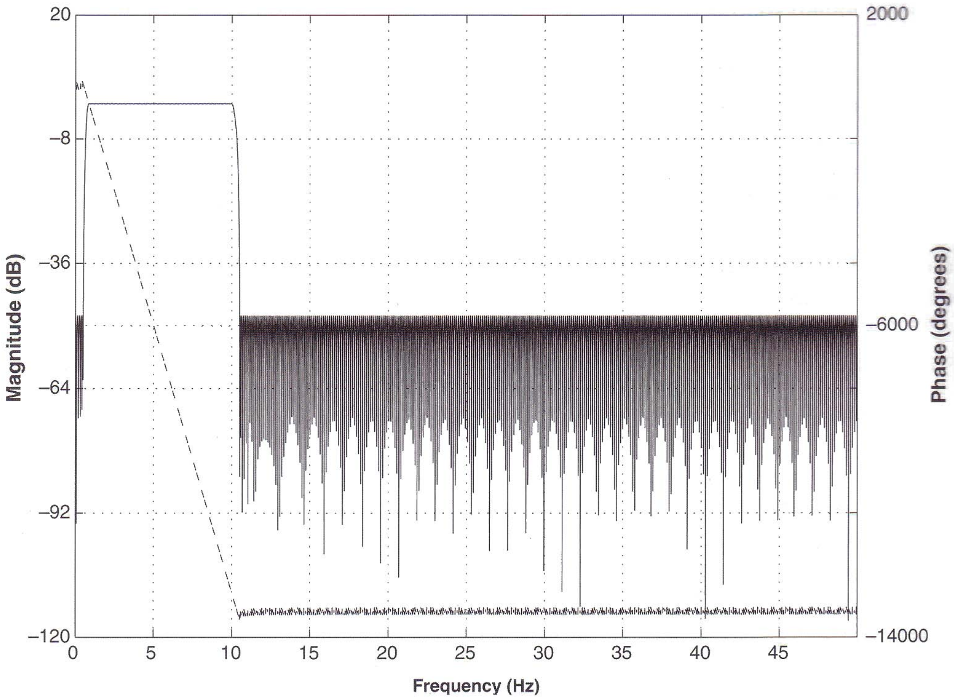
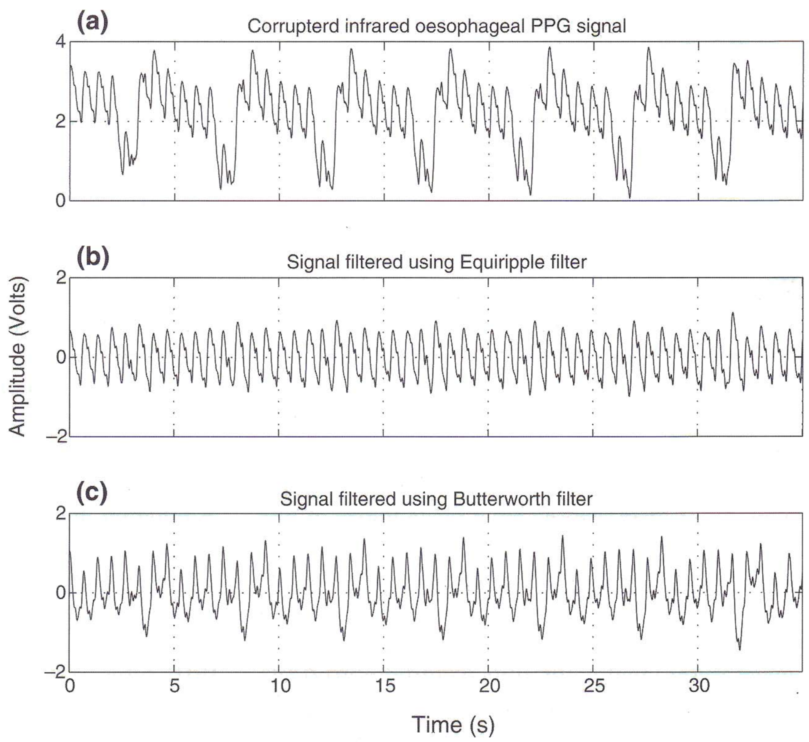


Fig. 2 **a** Oesophageal infrared ac photoplethysmographic (PPG) signal corrupted by the ventilator artefact; **b** filtered infrared ac PPG signals using the 766th order Equiripple filter; **c** filtered infrared ac PPG signals using the equivalent 10th order Butterworth filter



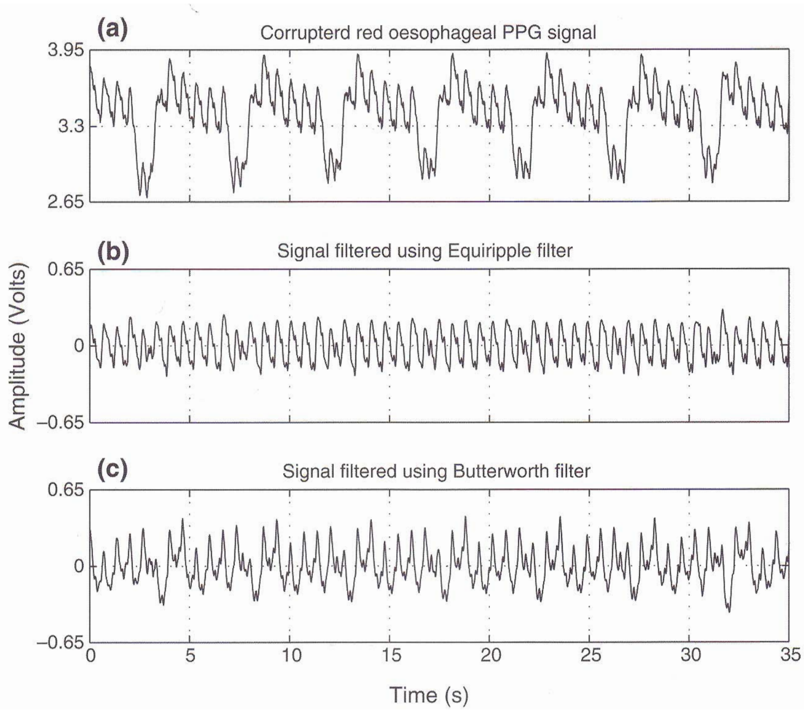


Fig. 3 **a** Oesophageal red ac PPG signal corrupted by the ventilator artefact; **b** filtered red ac PPG signals using the 766th order Equiripple filter; **c** filtered red ac PPG signals using the equivalent 10th order Butterworth filter

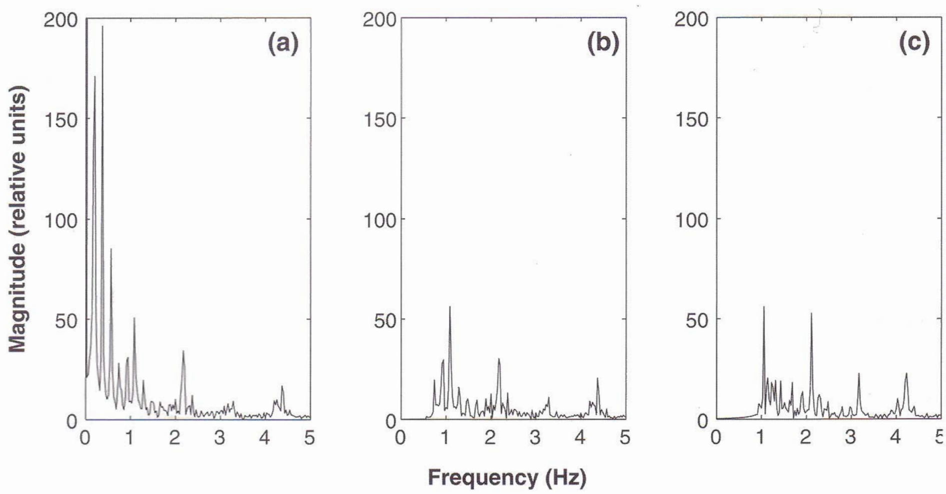


Fig. 4 **a** Magnitude spectrum of the raw oesophageal red PPG signal, **b** magnitude spectrum of the 776th order FIR Equiripple filtered oesophageal red PPG signal, **c** magnitude spectrum of the interpolated FIR (IFIR) filtered red oesophageal PPG signal

Table 1 Average improvement in signal-to-noise ratio (SNR) achieved by the finite impulse response (FIR) Equiripple filter at both red and infrared wavelengths for oesophageal photoplethysmographic (PPG) data from ten patients

	Artefact fundamental component (approx 0.2 Hz) (dB)	Artefact first harmonic (approx 0.4 Hz) (dB)
Red oesophageal PPG signal	57.96	52.26
Infrared oesophageal PPG signal	54.83	49.20

Table 2 Mean difference (FIR–Butterworth) in the SNR improvement between the FIR Equiripple and the equivalent Butterworth filter for oesophageal PPG data from ten patients ($p < 0.05$ in all cases)

	Artefact fundamental component (dB)	Artefact first harmonic (dB)
Red oesophageal PPG signal	19.02	36.43
Infrared oesophageal PPG signal	20.79	38.61

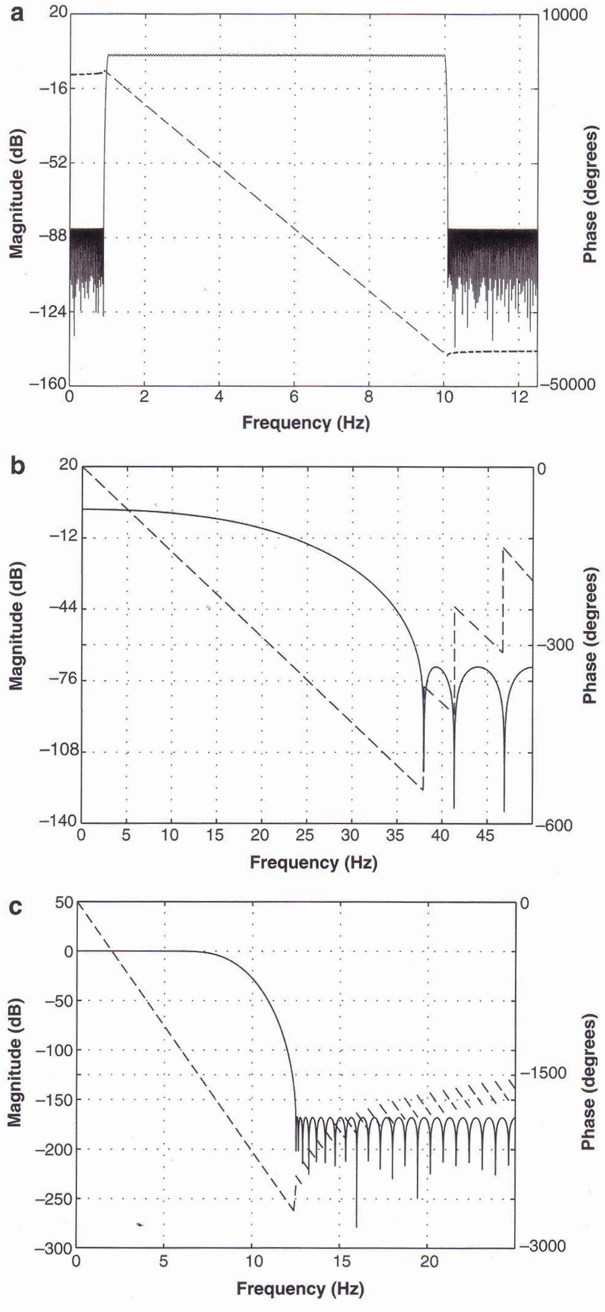


Fig. 5 **a** Magnitude and phase response of the 695th order IFIR filter; **b** 8th order image suppressor used at 100 Hz, **c** 60th order image suppressor used at 50 Hz

3.3 Results from the comparison between the 776th order FIR Equiripple filter and the 695th order IFIR filter

A direct comparison between the FIR [77,700 number of operations (multiplications per second)] and the IFIR [19,825 number of operations (multiplications per second)] filters was also performed, despite that the filters did not have exactly the same specifications. A comparison was deemed appropriate as it will demonstrate how two different filters with a similar level of complexity perform.

Results from the paired *t*-test between the FIR filter and the IFIR filter indicated that there was not significant difference between the average SNR improvement for both wavelengths. The mean differences in SNR improvement at each artefact component are presented in Table 5.

By looking at the specifications of the FIR filter (Subsect. 2.1) and the specification given in Sect. 2, that were used for the design of the IFIR filter, it can be seen that a direct comparison for the other harmonics of the ventilator artefact is not appropriate, as the cut-off frequency of the FIR filter is 0.5 Hz and its passband starts from 0.83 Hz. Whereas, the IFIR filter has a cut-off frequency of 0.87 Hz. Therefore, as shown by the spectrum of the filtered signals presented in Fig. 4 the FIR filter has caused negligible attenuation in the third harmonic of the artefact, as it lies in the transition region of the filter, but it has passed the fourth harmonic without any attenuation (as the frequency of this harmonic is higher than 0.83 Hz). Compare to this, the IFIR filter has significantly reduce all four harmonics of the artefact as shown in Fig. 4c.

3.4 Results on the effect of the developed filters on the estimation of SpO_2

Blood oxygen saturation values (SpO_2s) from uncontaminated (no ventilator artefact) PPG signals (220 s long) were estimated before and after filtering. Oxygen saturation values were calculated every 2 s which resulted in 110 SpO_2 values.

Over the period of 220 s the mean difference (± SD) of SpO_2 values (SpO_2 before filtering—SpO_2 after filtering) was –0.02 ± 0.11 and –0.12 ± 0.29 for the FIR

Fig. 6 **a** Filtered infrared ac PPG signals using the 695th order IFIR filter; **b** filtered infrared ac PPG signals using the equivalent 10th order Butterworth filter

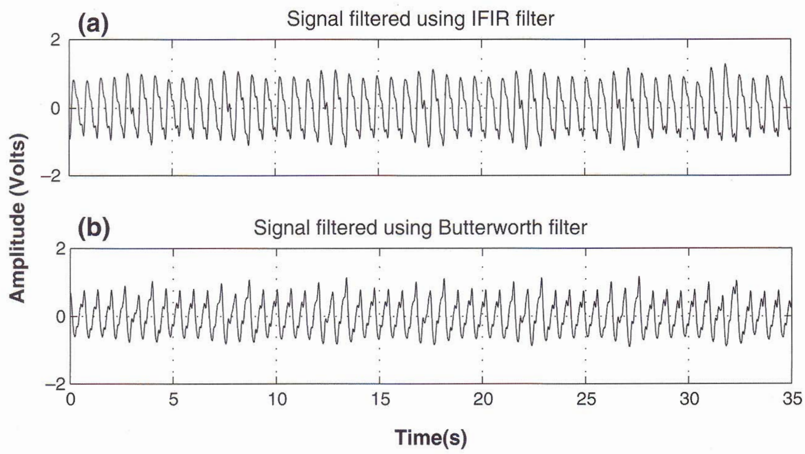
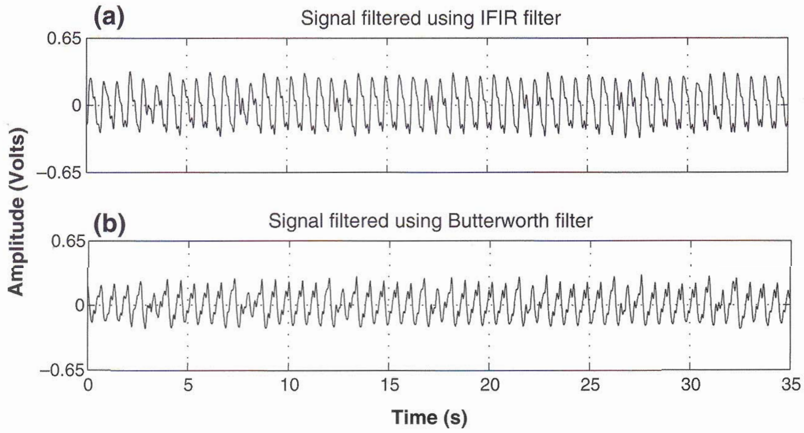


Fig. 7 **a** Filtered red ac PPG signals using the 695th order IFIR filter; **b** filtered red ac PPG signals using the equivalent 10th order Butterworth filter



and IFIR filter, respectively. This is also depicted graphically in Fig. 8.

A pair *t*-test analysis of differences between the SpO_2 results before and after filtering using both filters showed that there is no statistical significant difference.

4 Discussion and conclusion

The desirable filter specifications needed to suppress the ventilator artefact that contaminates the PPG signals from the lower oesophagus have been defined. An Equiripple FIR filter and an IFIR filter were implemented to meet these ideal specifications and, for comparison, two IIR Butterworth filters with cut-off frequencies equivalent to those of the Equiripple FIR and IFIR filters were also designed. The order of the FIR filter required to satisfy the desired specifications was calculated to be 2,774. Such a high order filter would not be easy to implement in software for real-time processing and, therefore, was abandoned. Instead, another FIR filter of order 776 was implemented which allows real time processing. The trade-off between the 776th and 2,774th order Equiripple FIR filters is real-time processing versus filter specifications; hence, the 776th order filter did not quite satisfy the original desirable filter specifications.

The response of the 776th order FIR Equiripple filter shown in Fig. 1 demonstrates that the phase response of this filter is linear in the passband. The Equiripple FIR filtered signals shown in Figs. 2b and 3b demonstrate clearly that the ventilator artefact has been reduced significantly without distorting the morphology of the PPG signal. The results for the equivalent 10th order Butterworth filter (Figs. 2c, 3c) show that the filtered PPG signal has lost its morphology and also that the ventilator artefact is not reduced to the same extent. The paired *t*-test (see Table 2) confirms that at both wavelengths the total improvement in SNR for the fundamental component of the PPG signal achieved by the Equiripple FIR filter is significantly greater than that for the Butterworth filter.

The second filter that was implemented was a 695th order IFIR filter. This filter satisfied the desirable

Table 3 Average improvement in SNR achieved by the interpolated FIR (IFIR) filter at both red and infrared wavelengths for oesophageal PPG data from ten patients

	Artefact fundamental component (dB)	Artefact first harmonic (dB)	Artefact second harmonic (dB)	Artefact third harmonic (dB)	Artefact fourth harmonic (dB)
Red oesophageal PPG signal	60.60	54.42	46.16	37.35	27.69
Infrared oesophageal PPG signal	60.96	54.06	45.32	36.65	26.18

Table 4 Mean difference (IFIR–Butterworth) in the SNR improvement between the IFIR and the equivalent Butterworth filter for the PPG data from the ten patients ($p < 0.05$ in all cases)

	Artefact fundamental component (dB)	Artefact first harmonic (dB)	Artefact second harmonic (dB)	Artefact third harmonic (dB)	Artefact fourth harmonic (dB)
Red PPG signal	20.45	22.79	25.68	28.92	25.10
Infrared PPG signal	19.59	21.99	25.11	27.17	23.62

Table 5 Mean difference (IFIR–FIR) in the SNR improvement between the IFIR and the FIR filters for the PPG data from the ten patients ($p < 0.05$ in all cases)

	Artefact fundamental component (dB)	Artefact first harmonic (dB)
Red oesophageal PPG signal	2.64	2.16
Infrared oesophageal PPG signal	5.26	4.54

initial filter specifications and also allowed real time processing. The responses of the IFIR filter and the image suppressors shown in Fig. 5 demonstrate that the phase response of this filter is also linear in the passband, hence there should be negligible phase distortion and the filtered PPG signal should retain its morphology. The results shown in Figs. 6a and 7a indicate that the IFIR filter has eliminated the ventilator artefact and has suppressed the first four components of the artefact (see Fig.4c). The Butterworth processed signals (Figs. 6b, 7b) show distortion of the PPG signal again, probably because of the non-linearity in the phase characteristics in the passband of the filter. The IFIR filter performs significantly better than the IIR Butterworth filter, not only in preserving the morphology of the signal but also in achieving greater improvement in SNR (see Table 4).

The 776th order FIR Equiripple filter performed very well in attenuating the fundamental and first harmonic of the ventilator artefact in the raw PPG signals, and hence in reducing the main cause of inconsistent and inaccurate SpO_2 estimation. Despite this, close examination of the spectrum in Fig. 4b shows that there are two artefact components, at

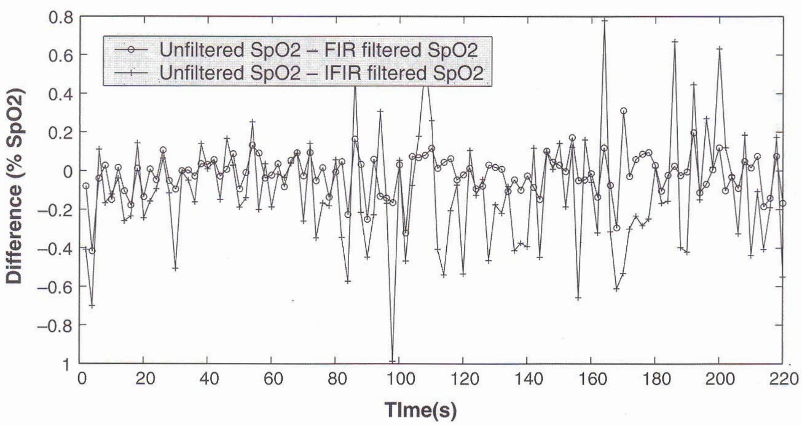


Fig. 8 Difference between the SpO_2 values before and after filtering using both, FIR and IFIR filters

approximately 0.7 and 0.9 Hz, present in the filtered signal that have magnitudes close to 50% of that of the ac PPG fundamental component. However, the 695th order IFIR filter successfully attenuated these two components as well, as is clearly shown in Fig. 4c. The effective elimination of these higher frequency components contributing to the ventilator artefact should allow a more accurate and consistent estimation of SpO_2. These results confirm that the IFIR filter is a better filter than the Equiripple FIR filter since it satisfies closely the desirable filter specifications originally proposed while also allowing real time processing.

The effect of the FIR and the IFIR filters on the estimation of SpO_2 from PPGs that are not affected by the ventilator artefact has been found to be insignificant. Although the IFIR filter performance is superior to that of the Equiripple FIR filter, the latter may be perfectly adequate for suppressing the ventilator artefact enough to allow reliable SpO_2 measurements in the lower oesophagus. Further clinical trials are needed in order to validate both filters in real time.

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